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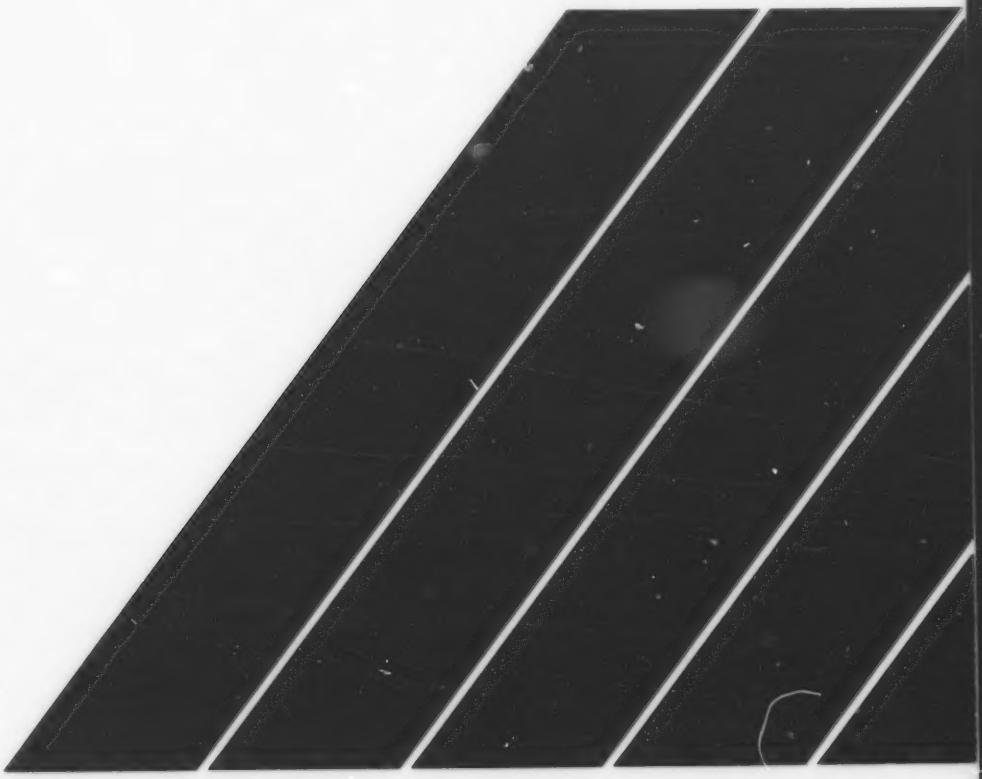
The Determination of Burst Proneness Indices for Lac du Bonnet Granite and Granodiorite

J.S.O. Lau

July, 1992.

Divisional Report MRL 92-070(TR)



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The Determination of Burst Proneness Indices for Lac du Bonnet Granite and Granodiorite

J.S.O. Lau[1]

Abstract

Results from previous cyclic loading post-failure tests on URL rock specimens show that Lac du Bonnet grey granite, granodiorite and pink granite have Burst Proneness Indices of 8.3-10.3, 10.5 and 8.3-15.7 respectively. The Burst Proneness Index is defined as the ratio of the strain energy retained to the strain energy dissipated during a single loading and unloading cycle of uniaxial compression.

Higher uniaxial compressive strength, p-wave velocity and tangent Young's modulus are related to a higher Burst Proneness Index and higher rockburst liability.

It should be noted that in the light of currently accepted rockburst mechanics, rockburst liability should be evaluated as burst or no burst situations by comparing the post-failure stiffness of the rock against the stiffness of the surrounding rock mass loading system. Although the validity of the Burst Proneness Index is questionable, it may be used as an indicator for the preliminary evaluation of the brittleness of the rock.

Keywords: rockburst, Burst Proneness Index, uniaxial compression, loading, unloading, strain energy, post-failure, stiffness, loading system

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Détermination des indices de propension à l'éclatement du granite et de la granodiorite de Lac du Bonnet

J.S.O. Lau[2]

Résumé

Les résultats d'essais précédents de mise en charge cyclique après rupture effectués sur des échantillons de roche du LRS montrent que le granite gris, la granodiorite et le granite rose de Lac du Bonnet ont des indices de propension à l'éclatement de 8.3-10.3, 10.5 et 8.3-15.7 respectivement. L'indice de propension à l'éclatement est défini comme le rapport de l'énergie de déformation retenu à l'énergie de déformation dissipée pendant un seul cycle de mise en charge et de retrait de la charge de compression uniaxiale.

Une résistance à la compression uniaxiale, un vitesse de l'onde p et un module de Young tangent plus élevés sont reliés à un indice de propension à l'éclatement plus élevé et à un risque de coup de toit plus élevé.

Il faut souligner qu'à la lumière des principes actuellement acceptés en matière de mécanique des coups de toit, le risque de coup de toit devrait être évalué sous forme de situation d'éclatement ou d'absence d'éclatement par comparaison de la rigidité après rupture de la roche avec la rigidité du système de mise en charge de la masse rocheuse avoisinante. Bien que sa validité soit douteuse, l'indice de propension à l'éclatement peut être utilisé comme un indicateur dans l'évaluation préliminaire de la fragilité de la roche.

Mots-clés: coup de toit, indice de propension à l'éclatement, compression uniaxiale, mise en charge, retrait de la charge, énergie de déformation, après rupture, rigidité, système de mise en charge

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Introduction

As part of the Canadian Nuclear Fuel Waste Management Program (NFWMP), AECL Research is assessing the concept of immobilization and subsequent deep disposal of nuclear fuel waste in a vault in stable crystalline rock within the Canadian Shield. One of the most important goals of the Canadian NFWMP is to demonstrate the ability to predict, from a limited amount of data, the short- and long-term behaviour of rock masses surrounding the vault when they are submitted to changes of stress, temperature, humidity and other time-dependent factors (TAC, 1990). The construction and operation of AECL's Underground Research Laboratory (URL) in the Lac du Bonnet batholith, provide the opportunities for characterization techniques to be evaluated and modelling capabilities to be assessed. As part of the URL rock mass characterization program, the Canada Centre for Mineral and Energy Technology (CANMET), in conjunction with AECL Research, has been conducting laboratory studies of samples from the URL and the surrounding rocks to provide data on the host rock mechanical behaviour at small scale (Annor and Jackson, 1987; Jackson et al., 1989; Lau et al., 1991). This information is also required for use in vault modelling and design as well as in large-scale in situ experiments.

As in any deep underground excavation work in hard rock, one of the issues of concern in the design, construction and operation of the URL is the danger of rock spalling and rockburst under high in situ stress conditions. During the excavation of the circular shaft of the URL into the unfractured grey granite immediately above and below Fracture Zone 2, spalling of the shaft walls and pop-ups of the shaft bottom were observed (Martin, 1990). At the 420 Level where the stress is high (σ_1 = 55 MPa), many of the openings show spalling and well-bore breakout type features (Martin and Read, 1992). It is therefore necessary to assess the burst proneness of the rocks surrounding the URL and to examine the use of an index to indicate the burst liability for rock mass characterization. The index may also be found to be useful for comparing bursting liability of rocks for any future site selection program.

Burst proneness or brittleness of a rock can be evaluated by using various principles, e.g. brittleness based on strain ratio, brittleness based on energy ratio, brittleness from Mohr's envelope, brittleness from compressive and tensile strength, brittleness from macro- and micro-

hardness and brittleness from Protodyakonov impact test (Hucka and Das, 1974). The Burst Proneness Index (Singh, 1986), determined from the energy ratio during a single loading and unloading cycle in the pre-failure region of uniaxial compression, is the subject of this study. However, it should be noted that in the light of currently accepted rockburst mechanics (Hedley, 1987), indices based on pre-failure rock behaviour are not necessarily valid.

This report establishes the Burst Proneness Indices for the Lac du Bonnet grey granite, pink granite and granodiorite and discusses the use of the Burst Proneness Index for rock mass characterization. No test was conducted in this study. Cyclic loading test data from previous studies on the mechanical behaviour of the rocks were used to establish the index values.

Rockburst

Rockburst is defined as a violent and sudden failure of a definite rock mass volume into an underground excavation sufficient to hamper mining activity and which registers as a seismic event. It is an excavation induced violent rock failure accompanied by a release of energy in amounts sufficient to cause damage to the surroundings. The source of the released energy is a combination of part of the strain energy in the failed rock, a change of potential energy of the surrounding rock mass, and in some cases, minor slippage along rock contacts (Hedley, 1987). It is the seismic energy component of the released energy, which is responsible for the damage caused by rockburst. It is worth noting that in a rockburst, the strain energy is the amount of energy available to burst, not the controlling or triggering factor. For a rockburst to occur, the rock must have reached its peak strength and the post-failure stiffness of the rock must be greater than that of the loading system (surrounding rock mass). Thus, it would appear that the potential for rockburst should be evaluated as burst or no burst situations, based on site specific factors such as the geometry of the opening, rock mass and rock properties (Bétournay, personal communication).

Rockburst can be classified into three types: strain, pillar and fault-slip bursts. The reader is referred to CANMET Division Report MRL 87-118(TR) (Hedley, 1987) for detailed descriptions of these three types as well as the rockbursting concept and rockburst mechanics. The type of

rockburst concerning the URL and any future repository is the strain burst which, by definition, is caused by high stress concentration at the edge of mine opening, exceeding the strength of the rock.

Burst Proneness Index

Singh (1986) defined rockburst as a sudden manifestation of the release of elastic strain energy stored in the rock. He suggested that the tendency of the rock to burst depends on its ability to store elastic strain energy, which in turn depends upon the elastic properties of the rock. He proposed the use of the Burst Proneness Index as the burst liability indicator for the strain type of bursts. The Burst Proneness Index, η, is defined as the ratio of the strain energy retained, E_R, to the strain energy dissipated, E_D, during a single loading and unloading cycle (in the pre-failure region) of uniaxial compression performed on a rock core specimen.

$$\eta = \frac{E_R}{E_D} \qquad (1)$$

The total energy accumulated under uniaxial compression can be represented by the area below the stress-strain curve for loading in Figure 1. The total energy has two components: the strain energy retained which is recoverable upon unloading and the strain energy dissipated which is irrecoverable upon unloading. Numerical values of E_R and E_D can be evaluated from the areas under the loading and unloading curves. It should be noted that rocks are not perfectly linear elastic and therefore, only a portion of the energy represented by the area below the stress-strain curve is strain energy. However, for the purpose of this analysis, it is assumed that the error introduced by this difference is negligible.

Singh (1986) conducted a study of rockburst proneness on rocks in the Sudbury Basin in the Canadian Shield, including gneiss, quartz diorite, granodiorite, gabbro, diabase, granite and schistose. He proposed the following scale for the bursting liability of those rocks:

$\eta < 10$ low bursting liability

$10 \leq \eta \leq 15$	medium bursting liability
$\eta > 15$	high bursting liability

Kidybinski (1981) used the same index to classify the potential liability of coal seams to create rockburst hazards. He named it the strain energy storage index, W_{ET}, and suggested the following classification of coal seams in respect of bursting liability.

$W_{ET} \geq 5.0$	high bursting liability
$W_{ET} = 2.0 - 4.99$	low bursting liability
$W_{ET} < 2.0$	no bursting liability

The strain energy storage index is also widely used for rockburst prediction in coal mines in China (Mei and Lu, 1987).

The Burst Proneness Index is a pre-failure estimate of the potential for rockburst, and thus, deviates from the currently accepted practice which compares the post-failure stiffness of the rock against the stiffness of the loading system such as the surrounding rock mass. However, in the absence of an estimate of the rock mass stiffness and the final vault configuration, rock properties data obtained from cyclic loading compression tests on exploratory cores may provide some insight into the brittleness of the rocks, mainly in terms of energy released, for the comparison of sites. For the final design of the repository, burst liability must be evaluated by comparing the stiffness of the rock mass loading system for a particular site against the post-failure stiffness of the rock.

Burst Proneness Indices for Granite and Granodiorite

In this study, data obtained from previous cyclic loading post-failure tests on core samples (Lau and Gorski, 1991a; 1991b; 1991c) were used to determine the Burst Proneness Indices for the Lac du Bonnet grey granite, granodiorite and pink granite. In those tests, unloading and reloading cycles were performed in a stiff MTS 815 testing machine at 40-MPa increments of axial stress until the axial stress reached approximately 75% of the estimated peak strength.

Above that stress level, unloading and reloading cycles were performed at 0.063-mm increments of circumferential deformation.

Results from each of those tests consisted of many cycles in the pre-peak, peak and post-peak regions of the complete stress-strain curve. Kidybinski (1981), Singh (1986) and Mei and Lu (1987) suggested using a single loading and unloading cycle up to approximately 80-90% of the peak strength for the determination of the Burst Proneness Index. Since the objective of this study is to examine the use of the Burst Proneness Index, it is desirable to investigate the variation of the index value at different stages of the test. In this study, for each specimen, the Burst Proneness Indices for all loading and unloading cycles in the pre-peak and peak regions and up to 47 cycles in the post-peak region (with the exception of 3 pink granite specimens) were calculated, using Equation 1. The results are plotted against the number of cycles in Figures 2 to 10. Also shown in those figures are the corresponding plots of stress versus the number of cycles so that the burst proneness of the rocks can be related to the different stages of failure of the specimens.

For the grey granite and granodiorite specimens, the Burst Proneness Index increases with the number of cycles in the pre-peak region, and reaches a maximum value in the post-peak region, 1 to 4 cycles after the peak strength has been reached (Figs. 2 to 8). The maximum value in the post-peak region is taken as the Burst Proneness Index for the specimen. Using the scale suggested by Singh (1986), the Burst Proneness Index for the grey granite (Table 1) varies from 8.3 to 10.3, indicating low to medium bursting liability. For the granodiorite, the Burst Proneness Index determined from only one specimen has a value of 10.5, indicating medium bursting liability. The Burst Proneness Indices for the Sudbury granite and granodiorite, determined by Singh, have values of 8.84 and 12.95 respectively. There is a good agreement between the index values for the Lac du Bonnet grey granite and granodiorite and those for similar rocks in the Sudbury Basin. In the post-peak region, the Burst Proneness Index decreases only slightly with increasing number of cycles, indicating the burst liability of the grey granite and granodiorite changes very little in the post-failure region. In one case (specimen 401-S12-MB1-27.547), the Burst Proneness Index actually increases in the post-peak region. However, it should be noted that this analysis does not cover the entire post-peak region (only up to 53 cycles), and the index

value is expected to drop as the specimen approaches its residual strength. It is also interesting to point out that an abrupt drop in stress is often associated with a drop in the Burst Proneness Index (Figs. 2 to 8). An abrupt drop in stress is caused by the formation of small fractures and spalling in the specimen, accompanied by a release of stored strain energy, reducing the brittleness of the rock. However, as the specimen regains some of the strength after the drop, the Burst Proneness Index also regains the value it has before the drop.

The relationships of the Burst Proneness Index and the strength of the pink granite specimens to the number of loading and unloading cycles in uniaxial compression are shown in Figures 9 and 10. With the exception of specimen 101-004-HG2-43.650, the Burst Proneness Indices increase in the pre-peak regions, reaching their maximum values at stress levels equal to approximately 55-72% of the peak strengths, and then decrease with increasing number of cycles. For specimen 101-004-HG2-43.650, high index values are observed at the first and second cycles, at stress levels equivalent to approximately 25-48% of the peak strength. Again, the maximum values are taken as the Burst Proneness Indices for the pink granite specimens. These values (Table 1) vary from 8.3 to 15.7, indicating low to high bursting liability. Post-peak data are available for only one pink granite specimen. Figure 9 shows the post-failure behaviour of the pink granite is characterized by a slight decrease of the index value with decreasing strength.

It is interesting to point out that the maximum index values for the pink granite specimens are found in the pre-peak regions, while those for the grey granite and granodiorite specimens are found at a later stage of failure in the post-peak regions. The discrepancy might be due to the effect of sample disturbance in the form of stress-induced microcracks in the grey granite and granodiorite specimens, rendering those specimens more brittle in the post-failure state. More research work is needed to address this issue.

Burst Proneness Index and Mechanical Properties

The results of the Burst Proneness Index, uniaxial compressive strength, p-wave velocity and tangent Young's modulus for each of the grey granite, granodiorite and pink granite specimens are presented in Table 1. The Burst Proneness Index is also plotted against the uniaxial

compressive strength, p-wave velocity and tangent Young's modulus in Figures 11 to 13 respectively. Specimens with a higher uniaxial compressive strength, p-wave velocity and tangent Young's modulus were found to have a higher Burst Proneness Index, which translates into higher bursting liability. As discussed earlier, the ability of the rock to store strain energy depends upon its elastic mechanical properties. A higher capacity to store strain energy can be related to a higher p-wave velocity and modulus value as well as a higher strength, resulting in a higher Burst Proneness Index, which is evaluated from the accumulated strain energy.

Figures 11 to 13 also show that the pink granite has a higher uniaxial compressive strength, p-wave velocity and tangent Young's modulus and consequently a higher Burst Proneness Index than the grey granite and granodiorite. However, it should be pointed out again that the grey granite and granodiorite specimens, obtained from the 420 Level of the URL, are characterized by the presence of stress-induced microcracks. This suggests that the lower values of p-wave velocity, Young's modulus and Burst Proneness Index for the grey granite and granodiorite may be the result of sample disturbance, rather than properties of the rocks.

Conclusions and Recommendations

One of the major issues concerning the stability and long-term performance of a disposal vault deep in crystalline rock is the danger of rockburst and rock spalling. Rockburst and rock spalling, in the short term, can hinder the safe operation of the vault, and in the long term, can create fractures in the rocks surrounding the vault and the emplacement boreholes, which could provide new groundwater pathways to the surface. For a rockburst to occur, the rock must have reached its peak strength, and the post-failure stiffness of the rock must be greater than that of the surrounding rock mass loading system. Given such thinking, it would appear that rockburst liability should be evaluated as burst or no burst situations, based on site specific factors such as the in situ stress, excavation geometry, excavation rate, geological discontinuities, rock mass and rock properties.

In the light of currently accepted rockburst mechanics, the validity of the Burst Proneness Index, η, determined from the elastic hysteresis loop parameters of a single loading and unloading cycle

in uniaxial compression, may be questionable. However, during preliminary site investigation, when only rock properties data are readily available, the Burst Proneness Index may be used as an indicator for the preliminary evaluation of the brittleness of the rock.

The Burst Proneness Indices for the Lac du Bonnet granite and granodiorite have been determined as follows:

grey granite	$8.3 \leq \eta \leq 10.3$	low to medium bursting liability
granodiorite	$\eta = 10.5$	medium bursting liability
pink granite	$8.3 \leq \eta \leq 15.7$	low to high bursting liability

Using the scale proposed by Singh (1986), there is a reasonable degree of correlation between the Burst Proneness Indices and the behaviours of the rocks at the URL. Spalling of the shaft walls and pop-ups of the shaft bottom as well as spalling in some openings were observed, but no violent rockburst occurred in the rocks.

The validity of the Burst Proneness Index could certainly be improved, if a relationship can be established between the Burst Proneness Index and the post-failure stiffness of the rock. The complete stress-strain curves for these specimens (Lau and Gorski, 1991a; 1991b; 1991c) show that these rocks exhibit class II post-failure behaviour with very high post-failure stiffness. Even without considering the stiffness of the surrounding rock mass loading system, one could assume it is probably a rockburst situation, should the local stress concentration exceed the peak strength of the rock. This suggests that all the index values (8.3 to 15.7) determined in this study can be related to a rockburst situation. However, it is known that the post-failure stiffness of rocks could be influenced by the loading rate. Rummel and Fairhurst (1970) found that for Tennessee marble, the slope in the post-failure portion of the complete stress-strain curve decreased with increasing strain-rate. The effect of loading rate on the post-failure stiffness of the rock must therefore be included in any study on rockburst liability.

As a heavily instrumented rock mass with considerable corresponding rock properties data, the URL provides an excellent opportunity for the study of rockburst. It is recommended to conduct

a more detailed study on the burst liability of rocks surrounding the URL by comparing the stiffness of the rocks against that of the rock mass loading system, based on in situ stress, opening geometry, rock mass and rock properties.

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Table 1. The uniaxial compressive strength, p-wave velocity, tangent Young's modulus and burst proneness index for rocks.

Specimen Identification	Rock Type	Uniaxial Compressive Strength (MPa)	P-wave Velocity (km/s)	Tangent Young's Modulus (GPa)	Burst Proneness Index η
401-S12-MB1-24.366	grey granite	135	2.990	44.30	8.3
401-S12-MB1-27.547	grey granite	137	3.330	46.39	9.2
401-S12-MB1-29.645	grey granite	142	3.730	49.38	9.8
401-S12-MB1-40.053	grey granite	143	4.478	50.50	9.1
401-S12-MB1-21.227	grey granite	151	3.895	50.13	10.3
401-S12-MB1-21.065	grey granite	154	3.893	50.96	9.8
401-S12-MB1-36.070	granodiorite	198	3.875	56.68	10.5
001-014-SM-N83-3.618	pink granite	160		68.27	11.8
101-004-HG2-43.520	pink granite	175	5.331	70.75	11.9
101-004-HG2-40.742	pink granite	177	5.392	64.84	8.3
101-004-HG2-43.650	pink granite	206	5.509	72.62	15.7

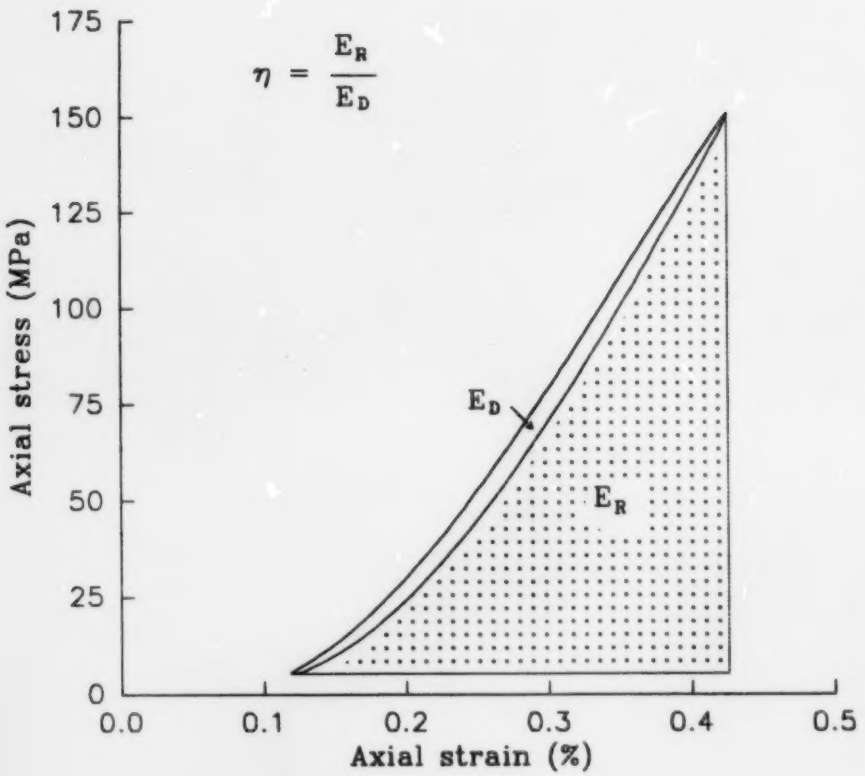

Figure 1. Typical stress–strain curve for loading and unloading.

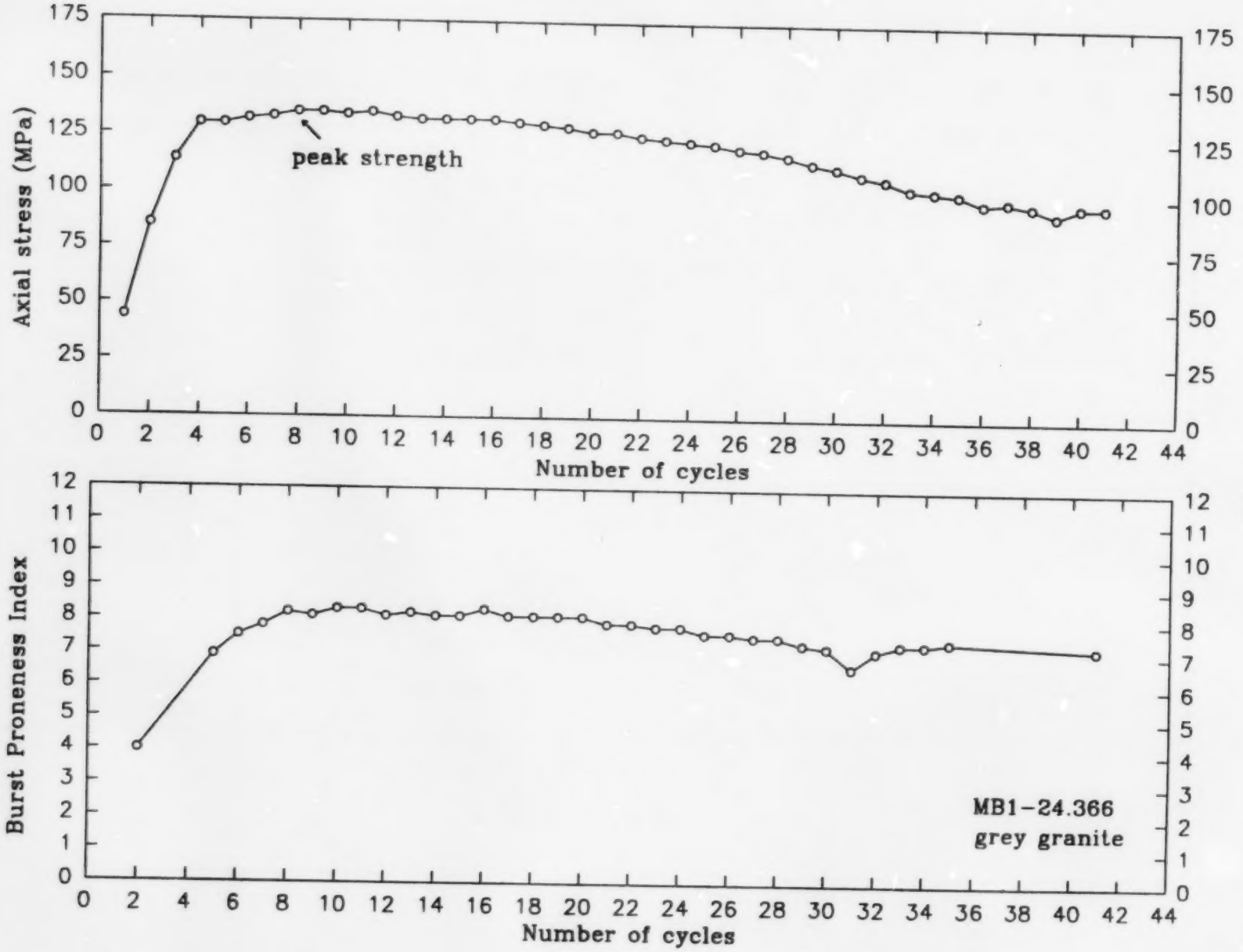

Figure 2. Burst proneness index and axial stress versus number of cycles (MB1-24.366)

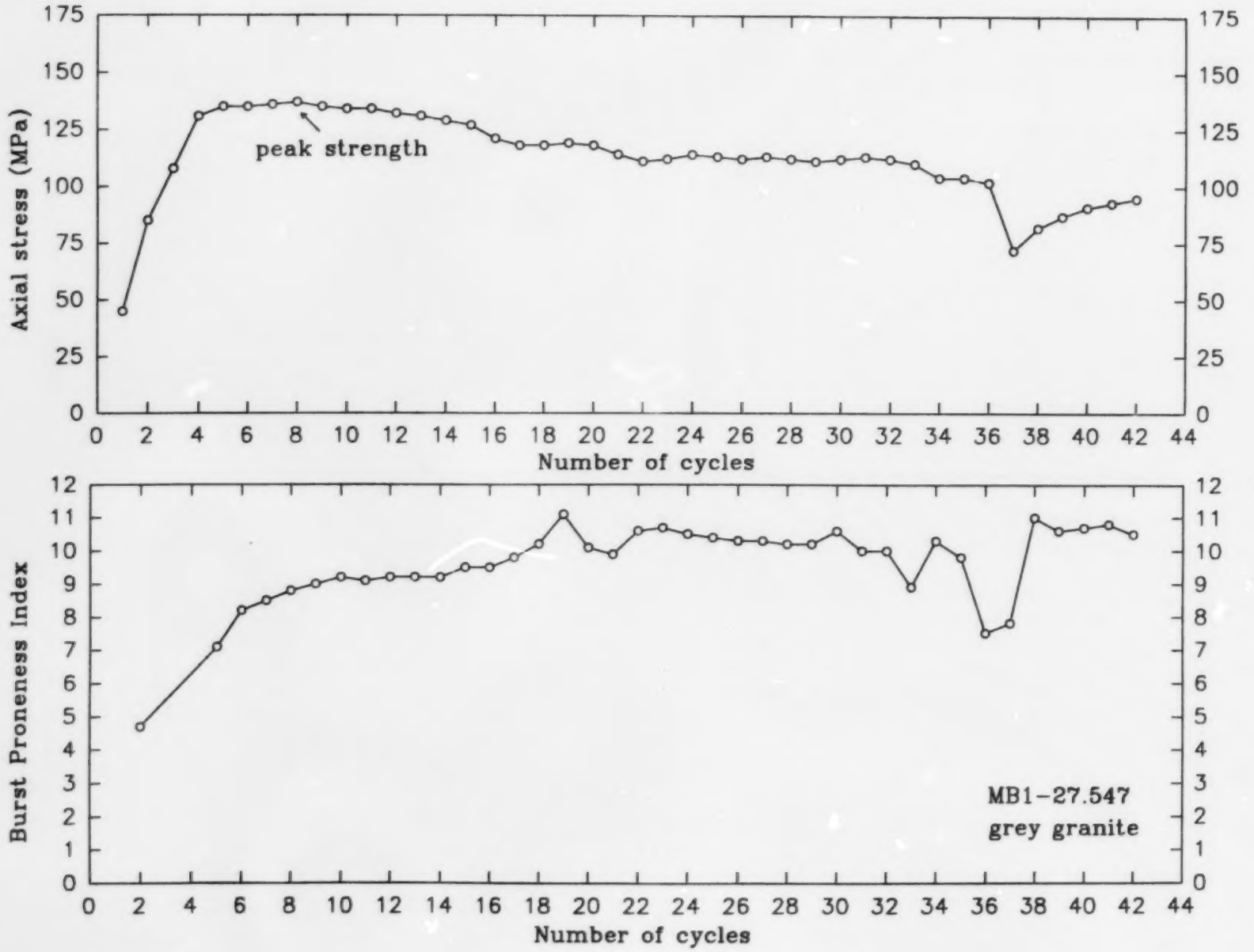

Figure 3. Burst proneness index and axial stress versus number of cycles (MB1-27.547).

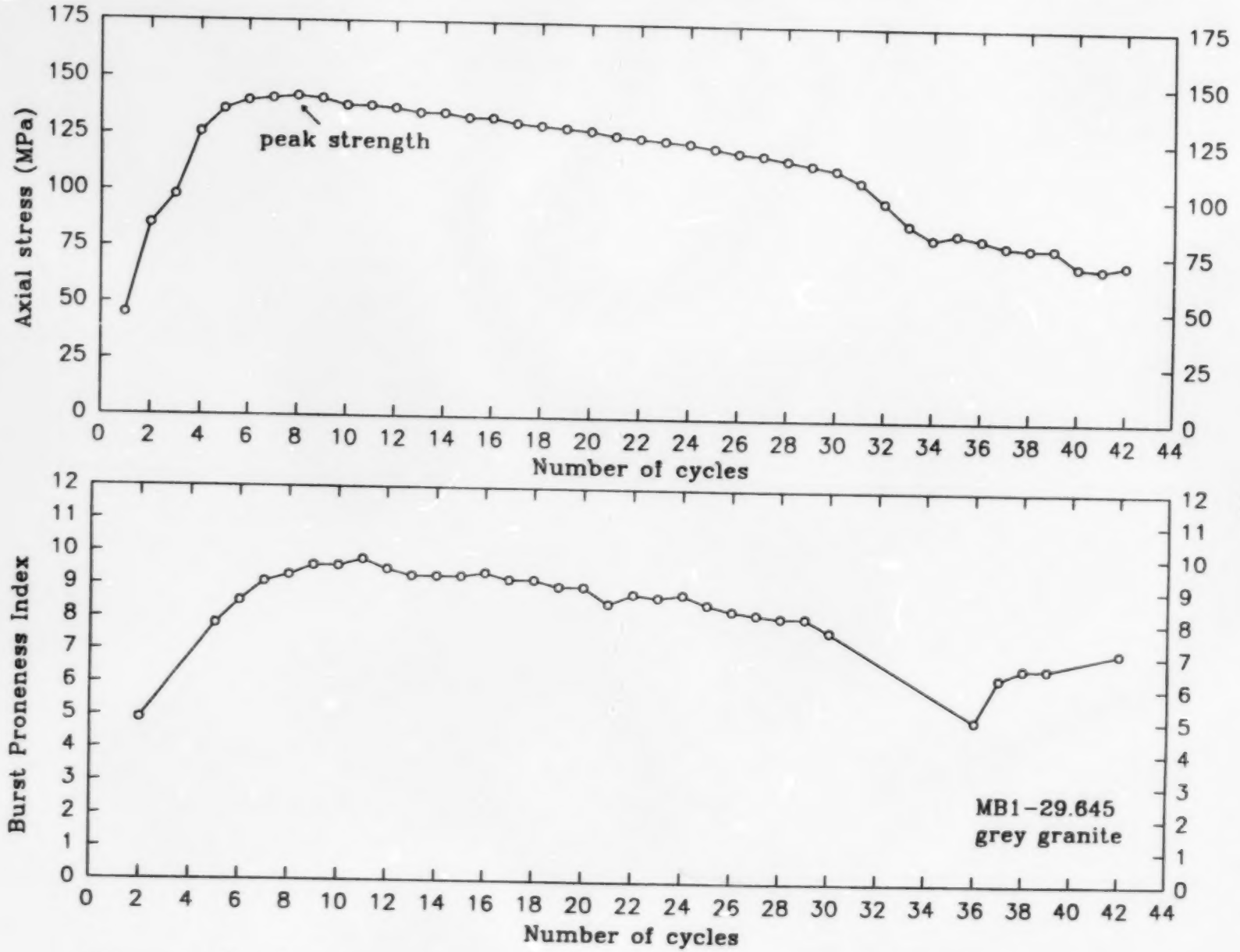

Figure 4. Burst proneness index and axial stress versus number of cycles (MB1-29.645)

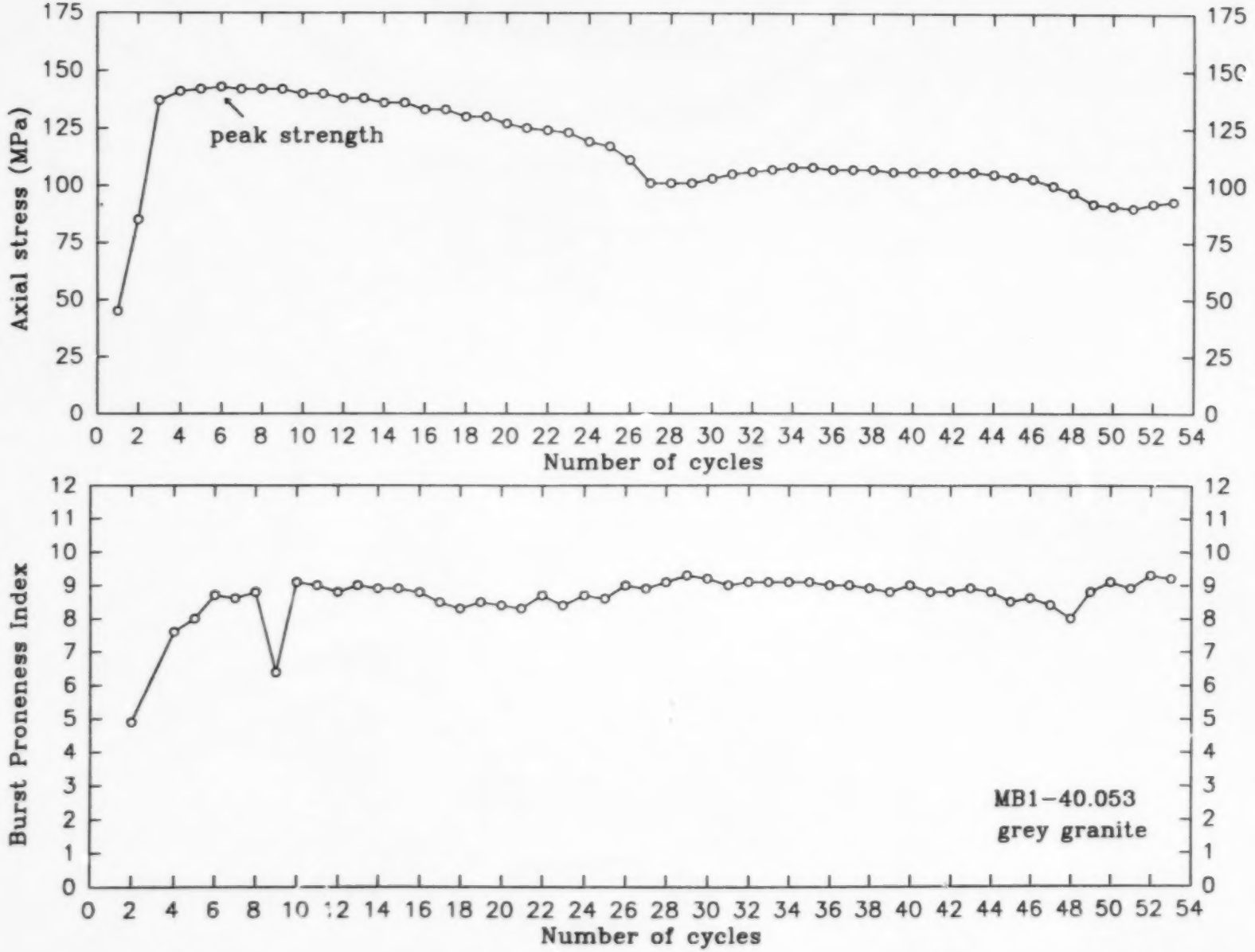

Figure 5. Burst proneness index and axial stress versus number of cycles (MB1-40.053)

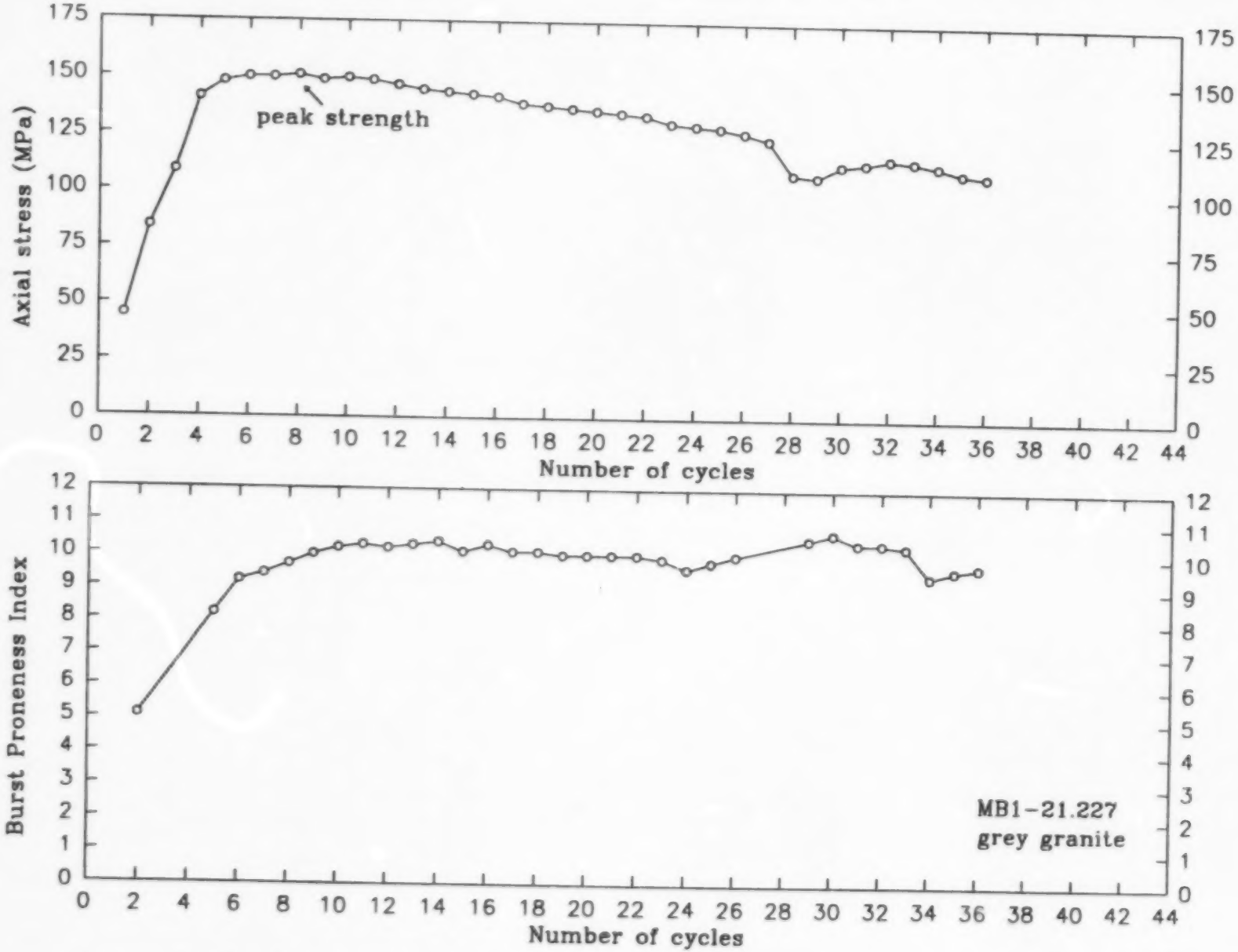

Figure 6. Burst proneness index and axial stress versus number of cycles (MB1-21.227).

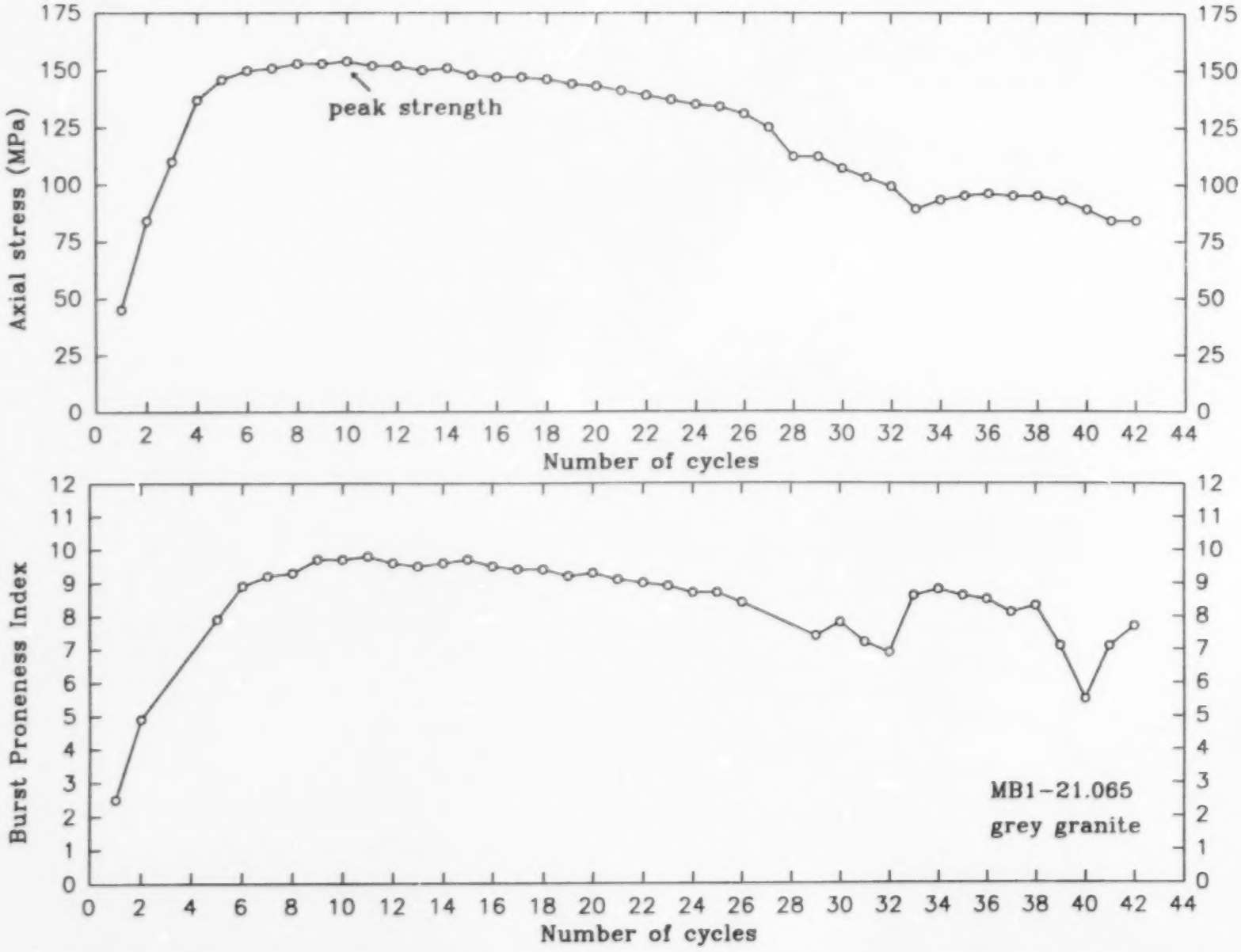

Figure 7. Burst proneness index and axial stress versus number of cycles (MB1-21.065).

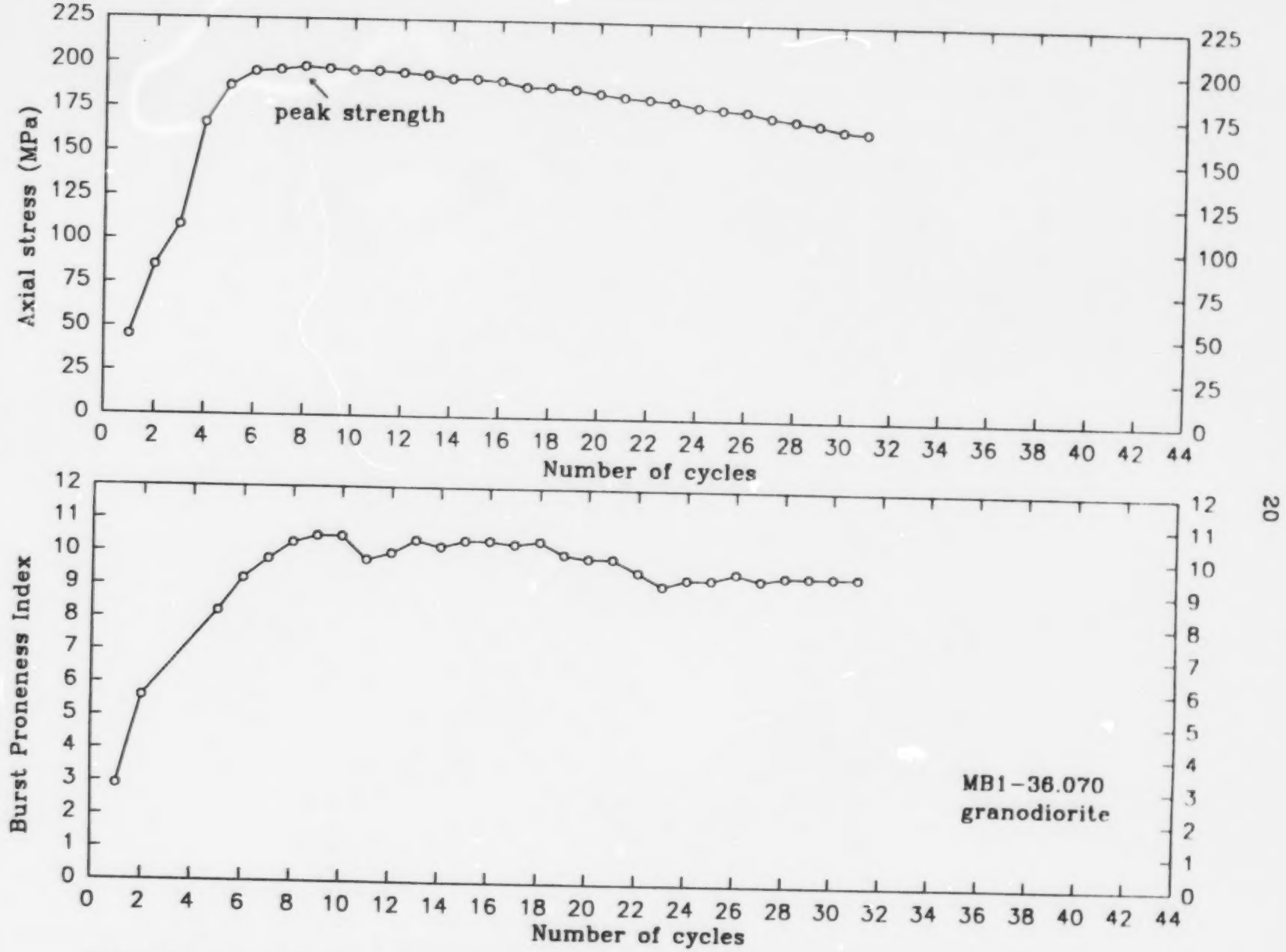

Figure 8. Burst proneness index and axial stress versus number of cycles (MB1-36.070).

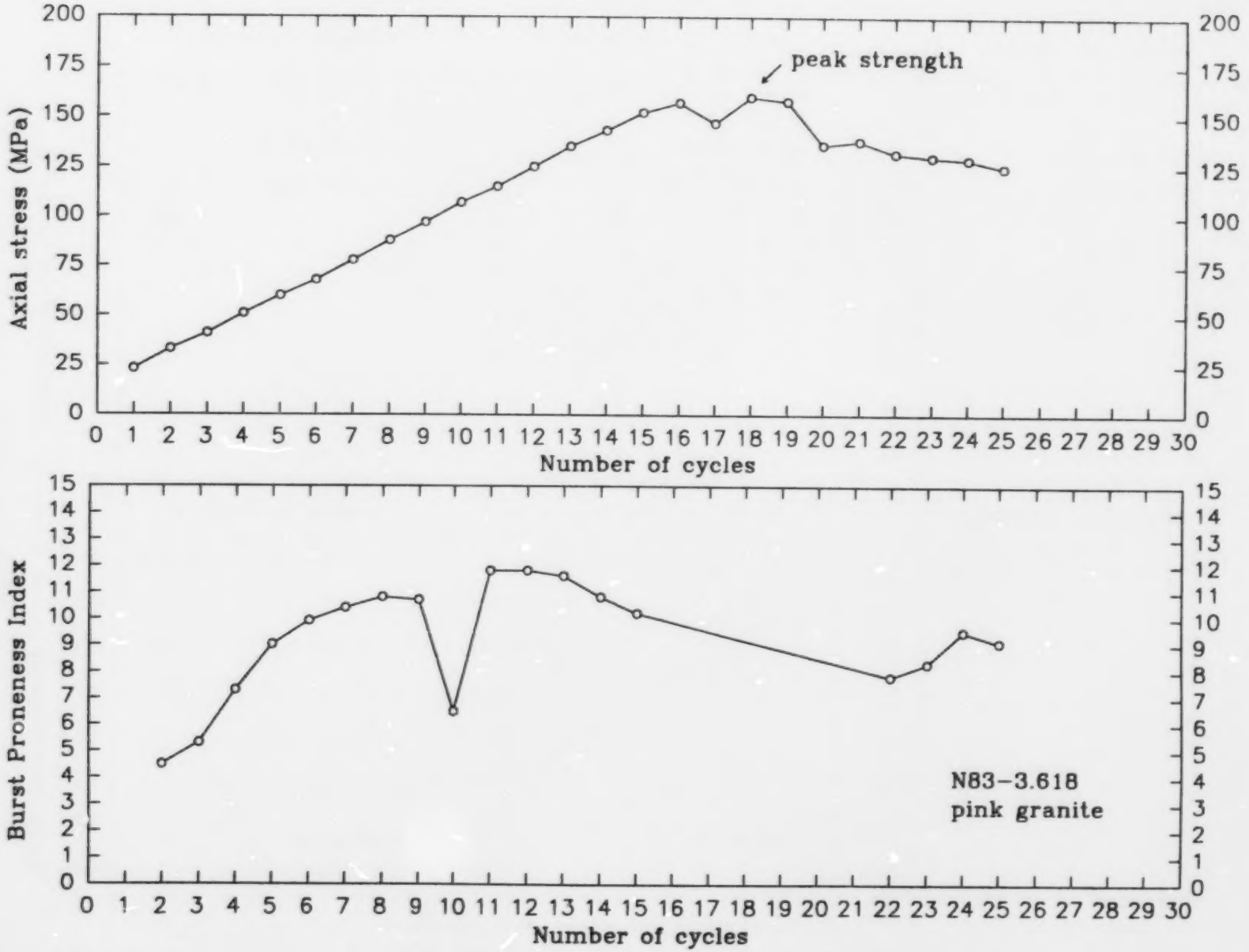

Figure 9. Burst proneness index and axial stress versus number of cycles (N83-3.618).

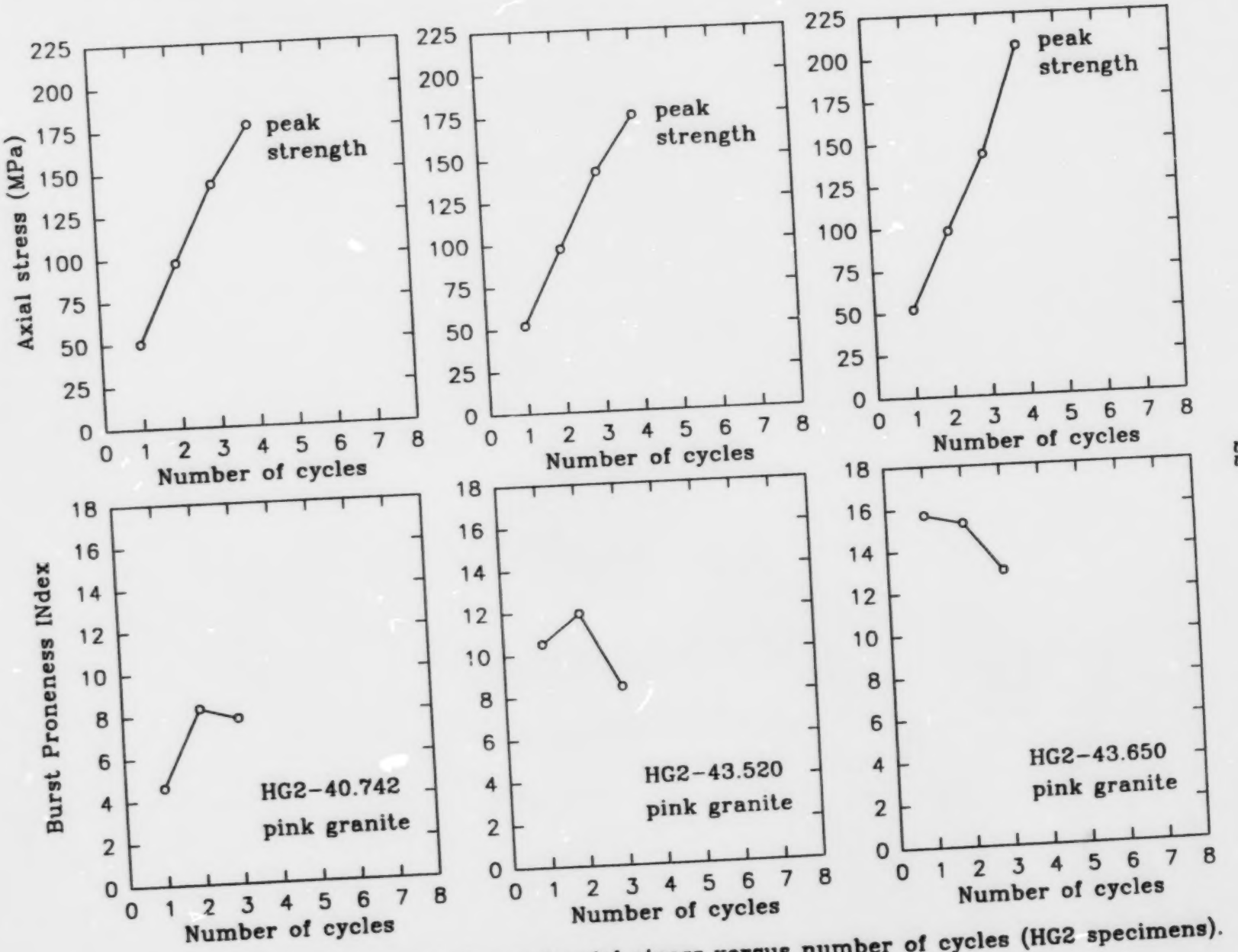

Figure 10. Burst proneness index and axial stress versus number of cycles (HG2 specimens).

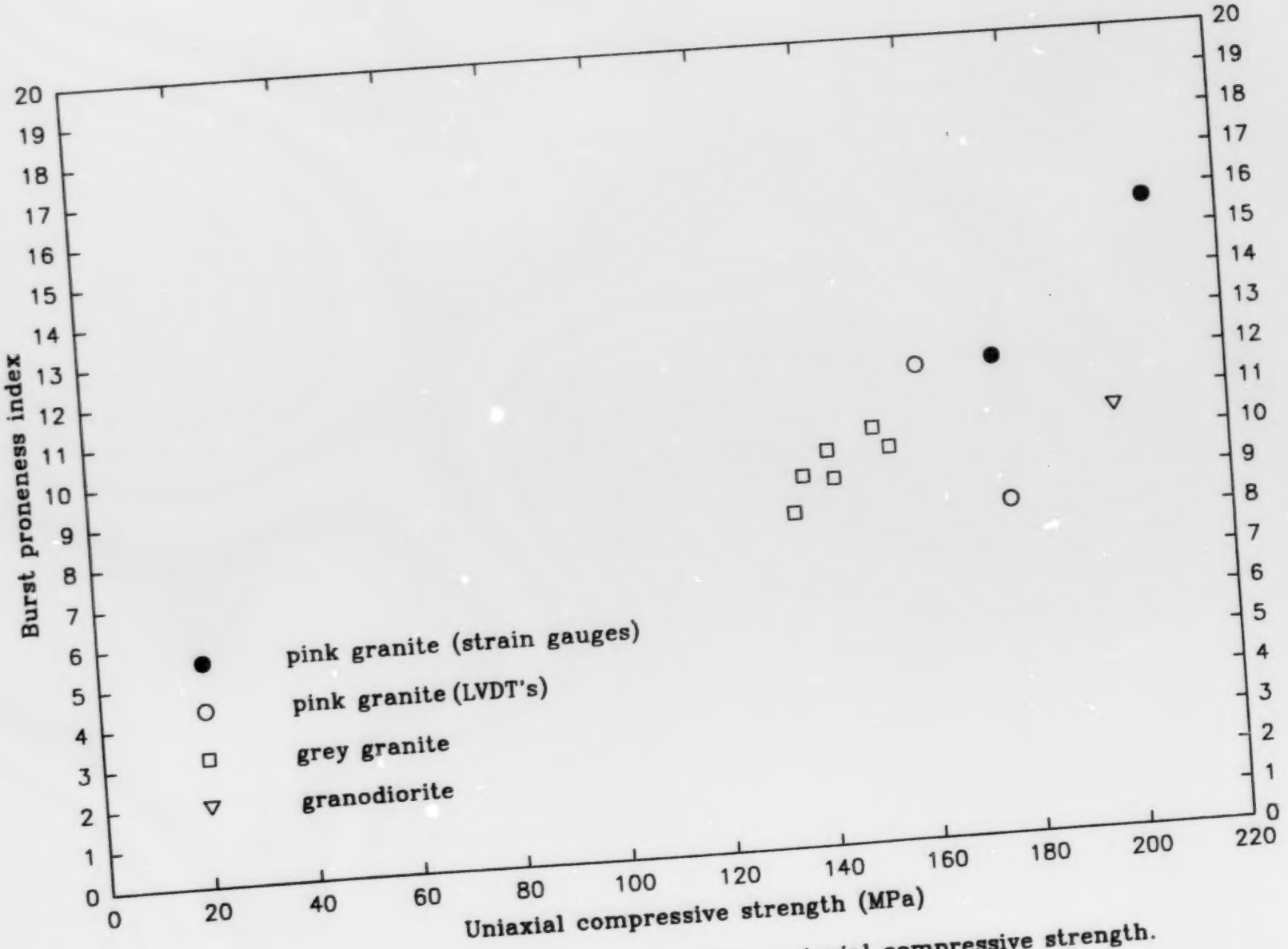

Figure 11. Burst proneness index versus uniaxial compressive strength.

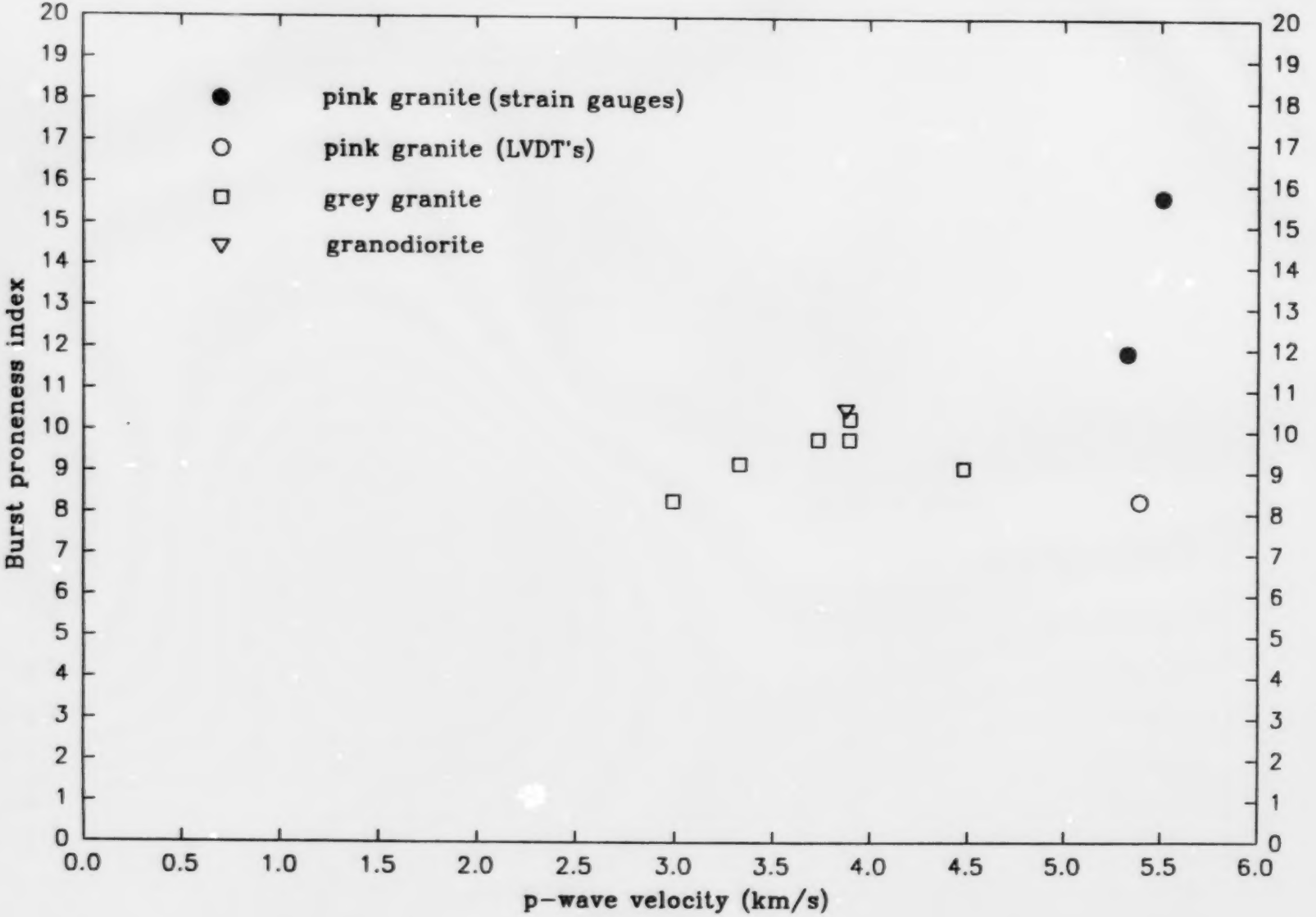

Figure 12. Burst proneness index versus p-wave velocity.

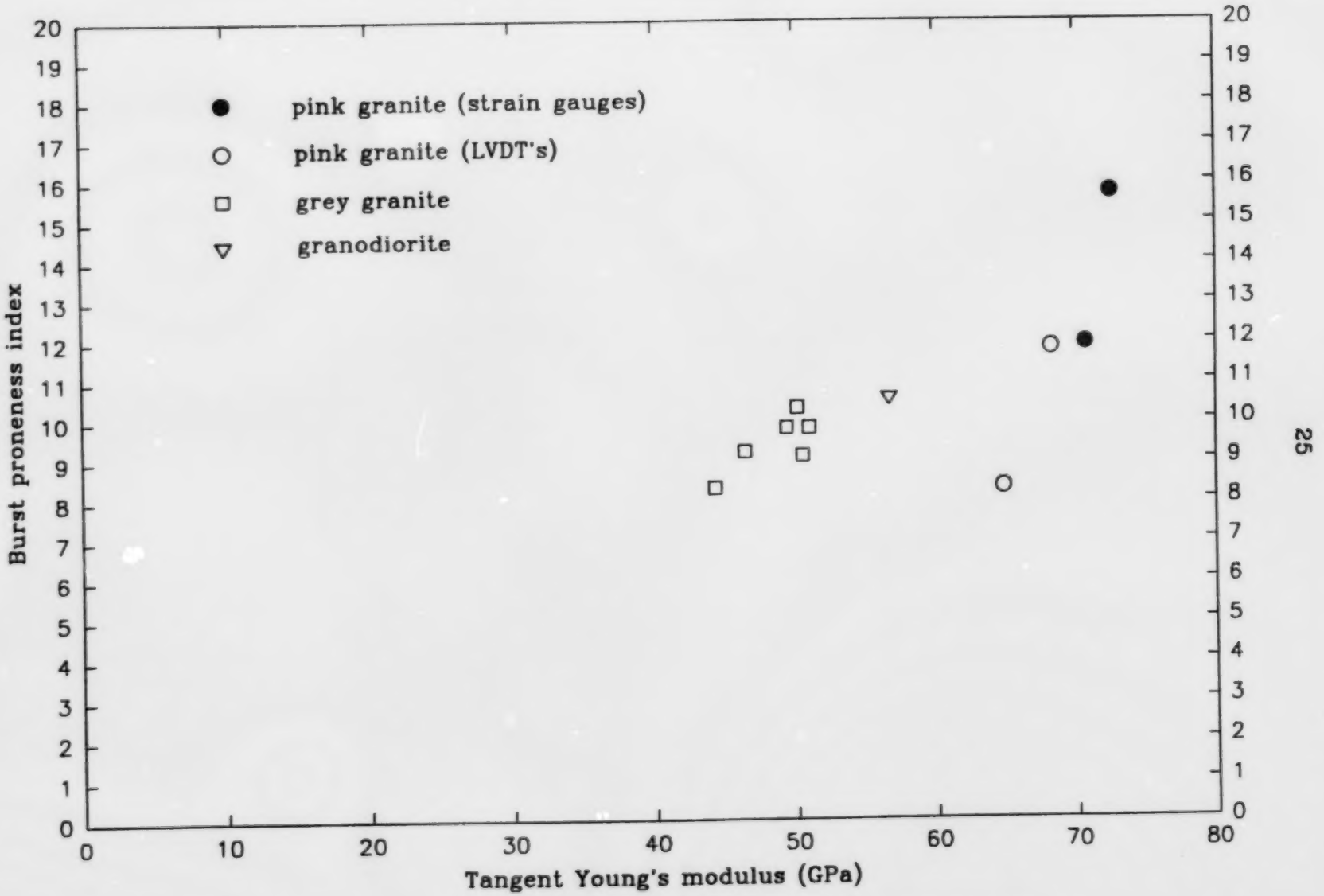

Figure 13. Burst proneness index versus tangent Young's modulus.